High-Resolution Imaging with Cross-Well Reflection Data

Spyros K. Lazaratos, James W. Rector, Jerry M. Harris, and Mark Van Schaack, Stanford Univ.*

SUMMARY

Cross-well data are definitely complicated. They contain a rich variety of wave modes producing a wavefield of intimidating complexity. This is probably the reason why traveltime tomography is by far the most popular type of processing applied to such data. Yet, other parts of the wavefield may be much more appropriate for achieving the high resolution necessary for accurate reservoir characterization.

In this study we enhanced the cross-well reflected wavefield through appropriate processing and used it for imaging a region between wells. Although our data were contaminated by strong, aliased tube waves, we were able to get a good tie with the well and resolution approaching that of the wireline logs. This leads us to believe that, with some improvements on the hardware and data acquisition, reflection cross-well imaging could become an extremely useful tool for reservoir characterization.

INTRODUCTION

In most cross-well studies, especially in those applied to real cross-well data, the direct arrival traveltimes have been used to invert for seismic velocities in the region between wells. Direct arrival traveltimes are definitely a robust observation that should be used whenever available. Still they represent a small fraction of the total information contained in the data. Although processing the full waveform is complicated, good quality reflection data present the potential for very high resolution imaging of reservoirs. This has been pointed out by several authors and a few real data studies have been published along these lines (Baker and Harris (1984), Iverson (1988), Beydoun et al. (1988), Abdalla et al. (1990)).

This paper presents the results of reflection processing applied to cross-well data in the frequency range of a few kHz for a well spacing of around 330 ft. The result of the processing is compared to synthetic seismograms generated from well logs. This comparison provides additional evidence that resolutions of the order of a few ft can be achieved for this range of frequencies. With further improvements reflection processing could provide a viable tool for detailed imaging of reservoirs.

DESCRIPTION OF THE DATASET

The cross-well data were collected at BP's test site located southwest of San Antonio near Devine, Texas. The site and data acquisition technique for a different dataset collected at the same site are described in Harris (1988). Two cased boreholes - Wilson 2 and Wilson 4 - were used. Each borehole is about 3000ft deep and their nominal separation is 330 ft. A sketch of the geology and the sonic logs for Wilson 2 and Wilson 4 are shown in Figure 1. Notice the similarity between the two logs, indicating lateral homogeneity.

The cylindrical piezoelectric bender transducer described in Balogh et al. (1988) was used as both a downhole seismic source and a receiver. The radiated wavelet was a short (approximately 1 msec) broadband waveform with a fundamental frequency of 2 kHz. Seismic waves with a frequency content ranging from about 200 Hz to 4000 Hz were recorded, although the received bandwidth varied depending on lithology.

The results presented in this paper were produced from just one common receiver gather. The receiver was positioned at a depth of 2355 ft. The sources were positioned over a range of depths beginning at 2140 ft down to 2800 ft at a depth spacing of 5 ft.

PREPROCESSING

The common receiver gather that we used is shown in Figure 2. We can see a clean direct compressional arrival and a reflection at about 2540 ft. The rest of the data are dominated by strong tube waves. The goal of the preprocessing was to extract and enhance the primary upgoing P-wave reflection arrivals using a combination of wavefield separation techniques, adaptive noise cancellation, and wavelet-shaping deconvolution.

The wavefield separation process had limited success in rejecting the strong tube wave arrivals. The 5 ft vertical sampling interval in the source well created an alias frequency of approximately 950 Hz. As the data contained frequencies from about 200 to 4000 Hz , much of the band contained aliased tube waves.

Additionally, the vertical sampling interval aliased shear and shear-converted waves at frequencies above 2000 Hz. For this reason, as well as lower signal-to-noise ratios at the higher frequencies, the extracted P-wave reflection wavefield was frequency bandpassed from 200 to 2000 Hz.

THE IMAGING PROCEDURE

The imaging algorithm that we used is a variation of the VSP-CDP mapping algorithm (Wyatt and Wyatt (1984)). It mainly involves two steps:

- Generation of maps assigning to every point in the image values of several quantities: depth of the receiver (source here since we are dealing with a common receiver gather) where a reflection from an interface at that location would be recorded, arrival time of the reflection, angle of incidence, geometric spreading, moveout of the event and angle of arrival at the receiver (source).
- Mapping the data on the image based on imaging operators defined from the quantities calculated before. This step includes a two-dimensional interpolation algorithm.

The algorithm allows us to easily incorporate geometric spreading corrections, AVO effects or radiation pattern corrections for the sources and receivers. For this study we have not applied any of those yet.

The velocity model is defined by picking and matching the direct arrival traveltimes. It is subsequently refined in a layer-stripping fashion to provide the best continuity of events and tie with the logs.

RESULTS - DISCUSSION

After application of the imaging algorithm to the preprocessed data a lateral mix of 20 ft was applied to attenuate residual aliased tube wave noise. In Figure 3 we show the image for the region nearest to the source well. We used only upgoing reflections, so we only image reflectors below the receiver (located at a depth of 2355 ft).

A synthetic seismogram created from the sonic log at Wilson 4 is shown for comparison. The upper part of the synthetic (down to a depth of 2625 ft) was created through the VESPA modelling software of Sierra Geophysics, to incorporate the effects of oblique incidence. The number of layers needed to appropriately block the whole interval of interest was larger than what our current version of VESPA could handle. So we calculated the lower part of the synthetic (below 2625 ft) as a normal incidence synthetic seismogram.

As a general observation we want to point out the amazing amount of information contained in the reflected wavefield. At the frequencies of investigation (kHz range) even the finer layers indicated by the well log have a detectible seismic response. This suggests that seismic data at these frequencies can provide resolution (at least vertical) similar to that of the sonic logs, that is, down to several feet.

The tie of our image to the log is good, although certainly not perfect. We have slight mismatches in several places but we can identify the events modeled by the synthetic. In some places the tie is excellent. Look for example at the interval between 2480 and 2620 ft. The doublet at 2480 ft is perfectly matched, as well as the spike a little bit below and essentially all the events up to the strong reflector at 2540 ft. Then we get the reflection from the top of the Eagle Ford shale at 2560 ft, the response of the heterogeneities inside the shale and the bottom of the shale at 2620 ft. Many of these features have thicknesses of the order of 3-5 ft.

In other depth intervals the tie to the synthetic is less exact. Moving to the top we approximately get the four peaks between 2430 and 2480 ft. We also get the four reflectors between 2380 and 2430 ft, although the upper three of those are dipping (the dip is an artifact of the mapping for the area very close to the receiver - at a depth of 2355 ft). Moving below the Eagle Ford shale we get a relatively quiet zone associated with the Buda limestone and then the top of the Del Rio clay at 2680 ft. We also get the reflection inside the Del Rio at 2700 ft. It is hard to correlate the rest of the events inside the Del Rio, but at least the character of the response is similar to the one indicated by the synthetic. We also seem to be getting the bottom of the Del Rio right at the bottom of our section.

Our section is still contaminated by tube wave noise, which makes interpretation away from the well ambiguous. In some places it is obvious that we have crossing events associated with coherent tube wave noise. Look for example at the events at 2440 ft and 2460 ft and at the bottoms of the Eagle Ford and the Del Rio that seem to be distorted by interfering noise. Subtler effects such as amplitude modulation are also apparent in many places.

Most of these effects are due to tube wave interference. We believe that the image would certainly benefit from lower levels of tube wave noise.

To illustrate the scale of the experiment and the detail obtained from the cross-well reflections we included in **Figure 3** a synthetic showing the image of the same area that would be obtained with typical surface seismic frequencies. We used a Ricker wavelet bandpassed between 10-60 Hz.

CONCLUSION

High frequency cross-well data contain a wealth of information beyond the first breaks. With good quality data and appropriate processing and imaging algorithms this information can be used to produce extremely high resolution (a few ft) images of reservoirs. This resolution is definitely beyond reach for surface seismic data.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of BP exploration and the Gas Research Institute (GRI).

REFERENCES

Abdalla, A. A., Stewart, R. R., and Henley, David, C., 1990, Traveltime Inversion and Reflection Processing of Cross-Hole Seismic Data: paper BG2.8 presented at the 1990 Annual Meeting of SEG, San Francisco, Sep.23 - 27.

Baker, L. J., and Harris, J. M., 1984, Cross-Borehole Seismic Imaging: paper BHG2.2 presented at the 1984 Annual Meeting of SEG, Atlanta, Dec.2 - 6.

Balogh, T. W., Owen, T. E., and Harris, J. M., 1988, New Piezoelectric Transducer for Hole-to-Hole Seismic Applications: paper DEV2.5 presented at the 1988 Annual meeting of SEG, Anaheim, Oct.30 - Nov.3.

Beydoun, W. B., Delvaux, J., Mendes, M., Noual G., and Tarantola, A., 1988, Practical Aspects of an Elastic Migration/Inversion of Crosshole Data for Reservoir Characterization: A Paris Basin Example: Geophysics 54, 1587 - 1595

Harris, J. M., 1988, Cross-Well Seismic Measurements in Sedimentary Rocks: paper DEV2.3 presented at the 1988 Annual meeting of SEG, Anaheim, Oct.30 - Nov.3

Iverson, W. P., 1988, Crosswell Logging for Acoustic Impedance: Pet. Tech. J., 75 - 82

Wyatt, K. D., and Wyatt, S. B., 1984, Determining subsurface structure using the vertical seismic profiling: In Toksoz, M. N., and Stewart, R. R., Eds, Vertical Seismic Profiling: Advanced Concepts, Geophysical Press

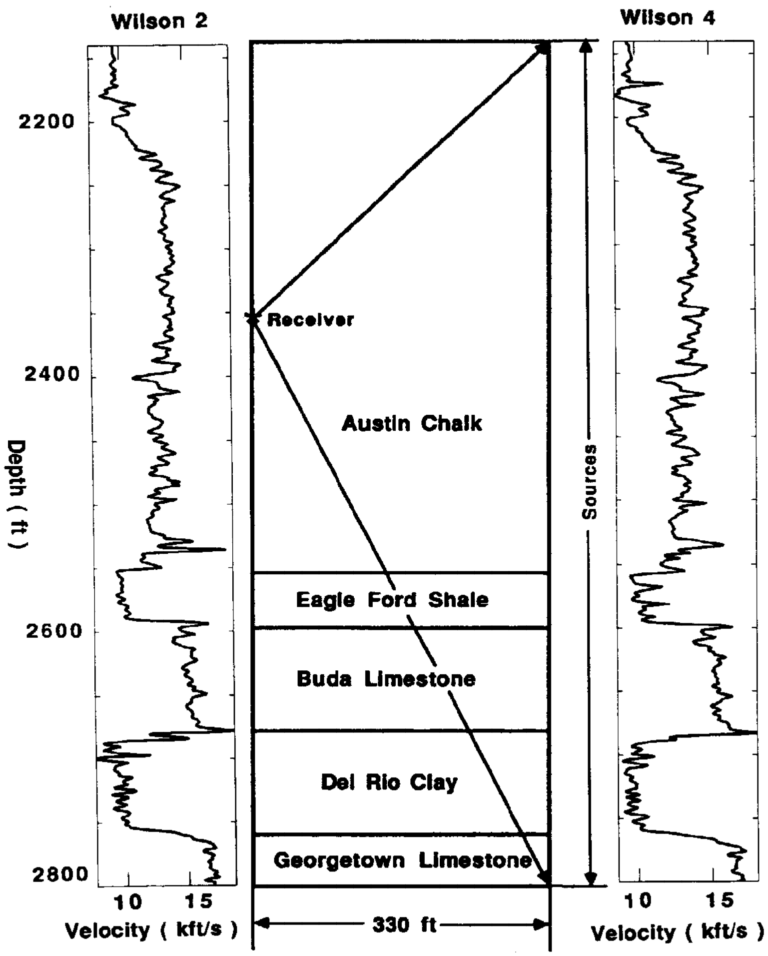

Figure 1. Sketch of geology and data acquisition geometry.

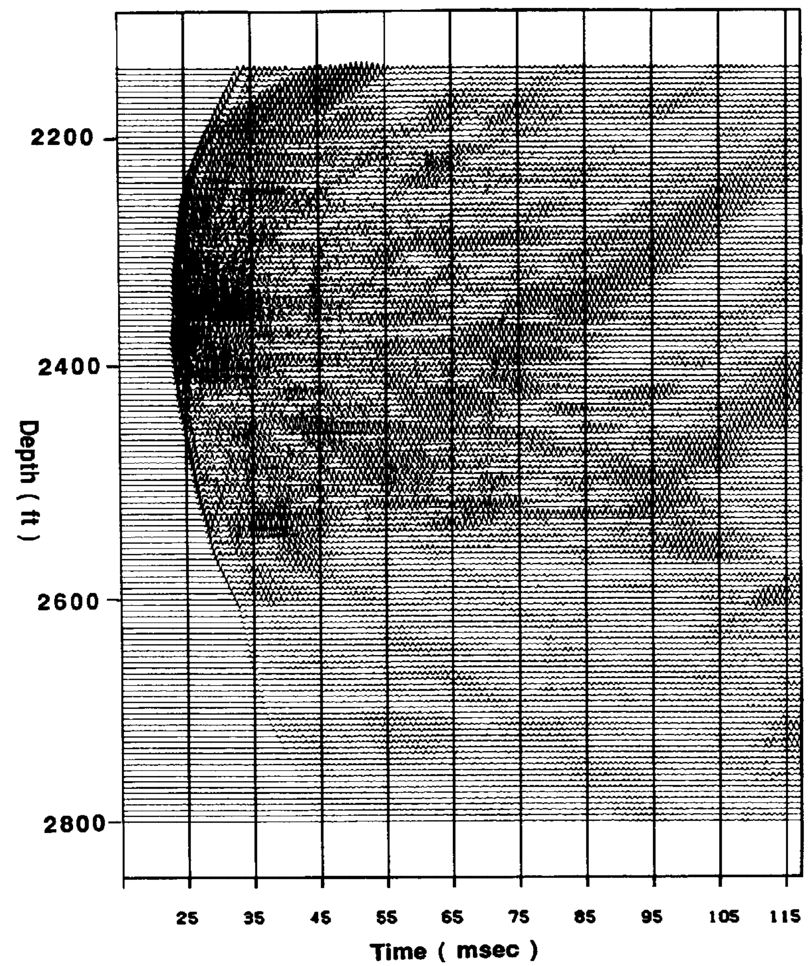

Figure 2. Raw data.

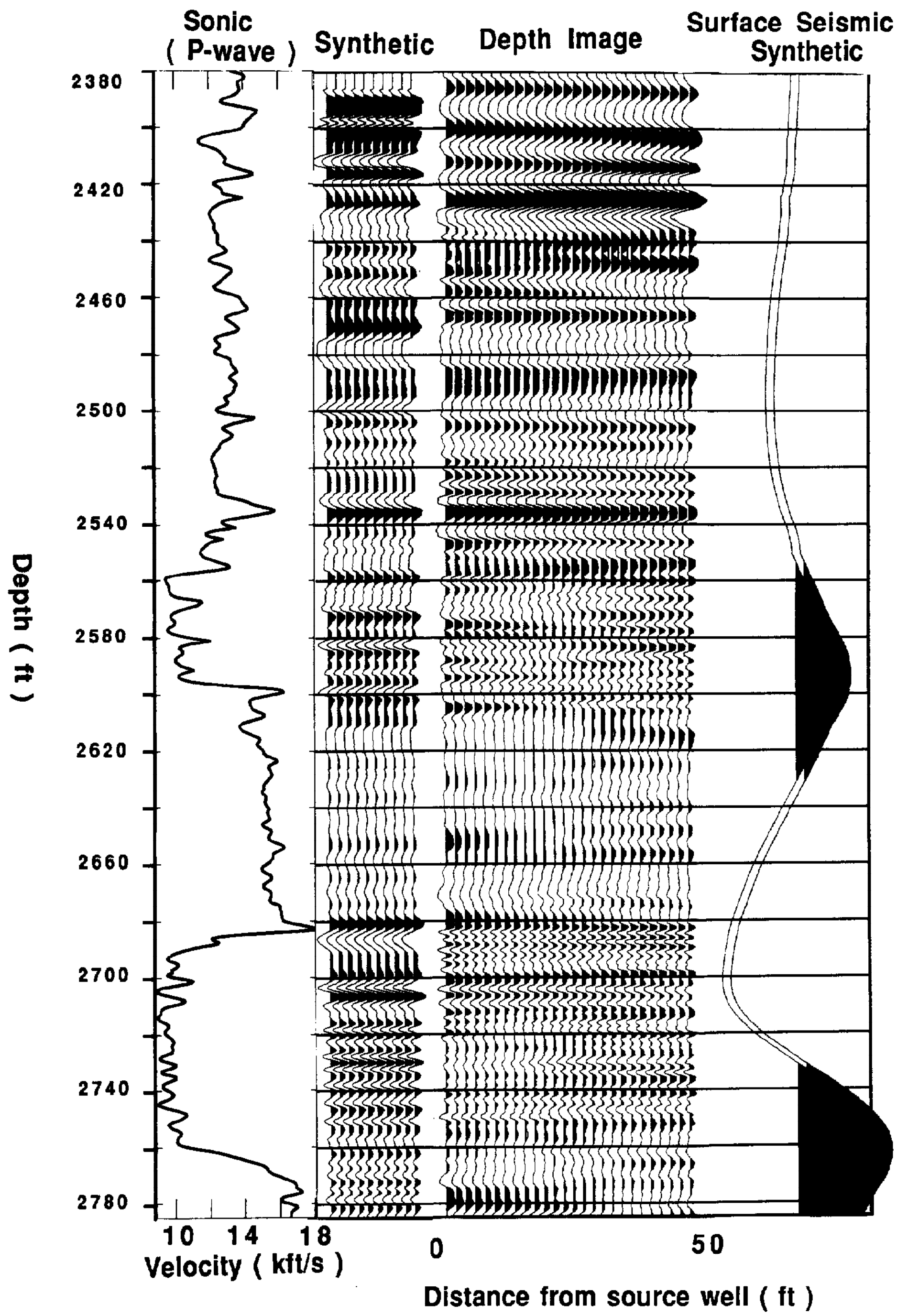

Figure 3. Result of imaging. The sonic log, a log-based synthetic and a synthetic for typical surface seismic frequencies are also shown.